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TAPERED WINGS, TIP STALLING, AND PRELIMINARY RESULTS FROM TESTS OF THE STALL-CONTROL FLAP

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SUMMARY

The general problem of stalling as affecting the safety of airplanes is considered. The increased difficulties associated with modern efficient wings, particularly with highly tapered wings and high-lift devices, are discussed and various means are considered of avoiding these difficulties with a minimum aerodynamic loss. Finally, preliminary data are presented for the stall-control flap and the application of these section data to wing design is briefly covered, mainly by means of an example.

GENERAL PROBLEM

Stalling.- The problem of avoiding excessive danger from the stall has been a recurrent one. Most airplane manufacturers dealt with the problem rather satisfactorily several years ago, either empirically or through a reasonably sound understanding of the phenomenon gained as the result of research work both here and abroad.

In genoral, the solutions embodied the use of marked static longitudinal stability, thus providing a definite warning of the approaching stall through the backward movement, position, and forces on the control column, together with a gradually developing stall secured either by allowing the upper or lower wing of a biplane to stall first or by using monoplanes with little or no taper and with "inofficient" wing-fuselage junctures, which further tended to bring about a gradually developing stall beginning at midspan. These measures tended to assure that tho stalled condition would develop progressively after a reasonably definite warning; furthermore, latoral control was often maintained up to or beyond the stall (wing maximum lift), owing to the fact that the essentially effective parts of the wing system, in relation to lateral stability and control, remained unstalled even after the angle of attack had exceeded that of maximum lift. Inasmuch as the pilot has little incentive to go beyond this point, such a solution was and still is considered satisfactory.

Modern trends.- With such satisfactory solutions in common use, attention has for the past few years been diverted from the problem of minimizing stalling dangers. Modern design trends are, however, bringing the problem back in an acute form. These trends are toward: Higher wing loadings and landing speeds; the substitution of efficient high-speed sections having more sudden and, hence, less desirable stalling characteristics; the almost exclusive use of tapered-wing monoplanes of increased taper resulting in an increased tendency for the stall to develop first near the wing tip where the effects are most harmful; the low-wing position, which contributes to reduced longitudinal stability with increasing lift; the use of "efficient" wing-fuselage junctures; and, finally, the use of certain high-lift devices. The high-lift device may further add to the dangers of tip stalling, add to balance and stability difficulties, and the commonly used flap usually causes a vicious section stall corresponding to a sudden, large, and often unsymmetrical loss of lift.

These trends are so far advanced that it now appears that many airplanes in common use cannot be considered reasonably safe, even for experienced pilots. The worst offenders may give no indication of an approaching stall. which, when it occurs, is manifested by a vicious uncontrolled rolling dive, that results from a sudden loss of lift on the right or left wing and a simultaneous loss of lateral control.

Recent investigations.- Practical methods of avoiding these conditions in modern types of airplanes have been sought. The investigations have proceeded mainly on the theory that the vicious stall may best be avoided in monoplanes by causing the wing to stall progressively from the center toward the tips. Not only are the sudden loss of lift and the violent roll thus avoided, but lateral control is maintained through the first stages of the stall and the tendency toward an upwash on the tail surfaces associated with the loss of lift near the center of the wing may be used to bring about a marked increase in longitudinal stability as the stall is approached.

In a preliminary investigation carried on in flight, sharp leading-edge strips extending out along the wing from either side of the fuselage were employed to bring about the desired symmetrical center-stalling characteristics. Wind-tunnel experiments with airfoils having sharp leading-edge sections over a small portion near their midspan were also made to indicate how the flight investigation should proceed. The flight investigations for the power-off condition showed that an airplane having vicious stalling characteristics could be improved, as expected, by thus bringing about a gradually and symmetrically developing center stall. The extreme maximum lift coefficient was, of course, slightly reduced but the practical gliding or approach speed was not increased; in fact, it was actually reduced.

Other methods.- Another proposed solution of the stalling problem should be mentioned: The limitation of the longitudinal control in order to prevent the wing from reaching maximum lift. Even aside from many rather obvious practical difficulties, this method cannot necessarily be relied upon to dispose of the problem. In any airplane approaching the conventional type there will always exist a minimum speed below which the airplane cannot be maintained in steady flight. Whether this speed is defined by control limitation, loss of lateral control, or the loss of lift beyond the maximum, maneuverability limitations must be accepted when it is reached. In one desirable case, for example, that of no limitation of control whatsoever with good lateral stability and control at maximum lift, the limitation is that the airplane in straight flight cannot make a turn either horizontally or to flatten the glide path in landing without first increasing the speed, which requires time and may require an amount of altitude not available.

If the speed is defined by longitudinal-control limitation, an additional maneuverability limitation must be accepted; the pitch angle cannot be increased. For example, if the airplane is over-controlled or disturbed in gusty air near the ground, it may be of vital importance to restrain the normal "stable" behavior of the airplane in order to prevent the nose from dropping into the ground, even though this procedure cannot flatten the glide path and may involve forcing the airplane much beyond the normal attitude of maximum lift. Such objections may be met by making the control stop quickly removable, but it then becomes a warning rather than a limitation. In any event, a warning of the approaching maneuverability limitation is required <u>before</u> it is actually encountered.

<u>Warnings</u>.- To be effective, the warning must be given at an angle considerably below that of maximum lift, because gusts or inertia effects may momentarily carry the airplane beyond the warning attitude. The difference in lift between that at the warning attitude and the maximum is, in some respect, practically the equivalent of a corresponding loss in the maximum lift coefficient. The amount of this loss depends on the character of the stall. If the stall is sudden and vicious, corresponding to the incipient spin with complete loss of control, the warning must be given very early to preclude the possibility that the stall may be reached inadvertently. In fact, some question exists as to whether the most vicious stalls should be considered acceptable at all; but, even if they are acceptable, the loss of effective maximum-lift is excessive. At the other extreme, when the stall is gradual and corresponds to no autorotational tendencies or loss of control, this effective loss of maximum lift may be practically eliminated. The warning may be given at an angle of attack several degrees before the maximum-lift attitude but, owing to the flat-top character of the lift curve, little loss of lift is involved.

<u>Present status</u>.- It therefore appears that, in principle, a study should be made of the original solution of the stalling problem mentioned in the first paragraph of this report. The practical application of this solution, however, involves the development of devices applicable to modern efficient monoplanes without appreciable sacrifice of efficiency and without loss of maximum lift. The first step has been to seek airfoil sections having gradual stalling characteristics but, unlike the sharp leading-edge sections, without reduced maximum lifts.

Airfoil sections having the gradual stalling characteristic, that is, a flat-top lift curve, have long been recognized as desirable in that they assure a gradually developing and symmetrical stall free from serious autorotational tendencies. Sections having rounded lift-curve peaks have, in fact, been available; for example, the N.A.C.A. 4412 (reference 1) and others of this class having moderately large cambers at a position near the middle of the section. This type of section, however, tends toward excessive drag at high speed. The most efficient high-speed sections, on the other hand, tend to show a sudden loss of lift at the stall.

PRESENT INVESTIGATION

The present wind-tunnel investigation began in an attempt to alter the efficient N.A.C.A. 23012 section with a view toward obtaining improved stalling characteristics. The alteration was accomplished by the deflection of a large-chord flap that will hereinafter be referred to as the "stall-control flap." The flap chord chosen was 60 percent of the airfoil chord (0.6c) so that the deflection of the flap tended to produce mean-line shapes somewhat like those of the airfoil sections N.A.C.A. 4412 and N.A.C.A. 6412.

The results of the preliminary tests proved very satisfactory. In fact, flat-top lift curves were so easily obtainable that the investigation was extended to include the application of the stall-control flap to sections having high-lift devices (in most instances a 0.2c split flap) of the type that previously had the most vicious stalling characteristics. Again it was found that, within limits, the vicious stall could be converted into the gradually developing desirable type and, in some instances, without a loss of maximum lift.

The next phase of the investigation consisted of analytical studies of the application of the stall-control flap to tapered wings and also of a few experimental checks in the variable-density wind tunnel of the predicted results. The use of these flap combinations on tapered wings leads to unusual flexibility of aerodynamic design because the large flap tends to control the lift distribution along the span, and the small flap controls the lifting capabilities of the various sections along the span. In fact, the Committee has built for experimental purposes a highly tapered wing having flaps of this type that may be varied to investigate the effects of changes in the load distribution and in the lifting capabilities along the span. With suitable flap combinations, it appears that gradual center stalling at high lift coefficients may be brought about even with highly tapered wings.

Several secondary results attend the use of the stall-control flap. The designer, however, must decide whether or not the various results, the value of which he may estimate from calculations, are justifiable on his particular design. This report is intended to be sufficiently complete to give the section characteristics required for these tapered-wing calculations for the stall-control flap used with or without a split-flap high-lift device. Except for a brief discussion and an example indicating one way in which the stall-control flap may be employed, the problem of its application to wing design will be considered outside the scope of this report and left, for the time being, to designers, who may make the necessary calculations from the data presented herein.

AIRFOIL SECTION CHARACTERISTICS

Tests.- The usual 5- by 30-inch duralumin models and test procedure (reference 2) were employed in the variable-density tunnel (reference 3) to obtain the desired section characteristics for the combinations with the stall-control flap. In most instances the basic airfoil section N.A.C.A. 23012 (references 4 and 5), was used, although in a few instances a thicker airfoil of the same family, the N.A.C.A. 23015 (reference 5), was employed.

The flap was formed by sawing the airfoil at the 40-percent station and attaching a thin steel plate let in flush on the lower surface, which formed a hinge by bending. Finally, the gap was filled with plaster of paris and carefully finished along a radius tangent to the upper surfaces of the front and back parts of the section. This procedure assured a smooth and fair upper surface having a radius of curvature above the hinge approximately equal to the airfoil thickness. The small-chord plain flaps were formed in substantially the same way.

In practice, it might be difficult to provide as fair an upper surface as that formed on the models. Furthermore, it was considered that the upper-surface shape, particularly in the neighborhood of the large flap hinge, might exert a marked effect on the character of the stall. For these reasons the three variations indicated in figure 1 were investigated for one flap combination. The results indicated surprisingly small, if not negligible effects, even when a break on the upper surface was made almost sharp to simulate a practical case such as a piano hinge along the upper surface.

Results.- The characteristics of the various flap combinations are presented in figures 2 to 7 and in table I. The usual graphic and tabular forms of presentation (reference 6) are employed except that, for compactness, several flap displacements are included on each plot and redundant curves or those presenting characteristics of minor importance such as C_p, L/D, and the lift peak at reduced Reynolds Number have been omitted. The most important results are given on the left-hand portion of the plots (lift curves for aspect ratio 6, effective Reynolds Number approximately 8,000,000). These curves indicate the character of the stall. A gradually developing stall is indicated by a rounded lift-curve peak. The actual presence of this progressive type of lift variation with angle of attack was checked by recording for each combination the actual variation of lift with angle of attack near the stall by an automatically recording electrical lift balance, which actually drew the lift-curve peak.

The stall as thus represented is, of course, for the rectangular wing of aspect ratio 6 rather than for the section. The section stall may be expected to develop less gradually, owing to spanwise progression effects included in the rectangular airfoil tests (reference 2), but some experimental evidence exists to indicate that the <u>section</u> stall will not be of a different character. Section lift curves, as required for tapered-wing calculations, may be derived from the presented C_L curves by the methods of reference 2, that is, each angle is reduced by 3.17 C_L degrees to obtain the curve of c_l against α_o, and $C_{L_{max}}$ is usually increased by the factor 1.07 to obtain the section value, $c_{l_{max}}$

The other important results are shown as section characteristics on the right-hand portion of the figures. The fully corrected (reference 2) section profile-drag results are given and the pitching-moment characteristics of each section are represented by $c_{m_{(a.c.)_o}}$, the pitching-moment coefficient of the section about the aerodynamic center of the undeformed section.

Results are given for several large-chord flap deflections (0°, 4°, 8°, 12°, 16°, 20°) and for each of several large-chord flap deflections with the 20-percent-chord split flap deflected various amounts (0°, 15°, 30°, 45°, 60°). A few combinations with a plain flap rather than a split flap are also included.

Discussion.- The most important results from the application of the stall-control flap are the change in the character of the stall, the change of the stalling angle, and the increase of lift at a given angle. The effectiveness in changing the character of the stall when applied to the N.A.C.A. 23012 is indicated by the lift curves in figure 2. A 4° deflection is not sufficient to remove entirely the sudden fluctuations of lift at the stall but the 8° and the higher settings show the desirable rounded lift-curve peaks. The most desirable shape is given in the neighborhood of 12°. At this deflection only a slight gain in $C_{L_{max}}$ is shown; however, the lift curve shape is improved, the stalling angle is reduced approximately 5°, and C_L at $\alpha = 0^\circ$ is increased from 0.09 to 0.88. This change in lift is approximately that expected from airfoil theory, the rotation of the flap being approximately 0.9 as effective as the rotation of the whole airfoil.

Other changes produced by the flap are shown in the right-hand part of figure 2. Moderate flap deflections show very slight changes in profile drag in the useful range of lift coefficients. The 12° deflection gives a pitching-moment coefficient at zero lift of -0.087, only a little more than the plain Clark Y airfoil. This pitching moment associated with the flap deflection is small as compared with that for an ordinary small-chord flap deflected to produce the same lift-curve displacement.

Figure 3 is included so that the action of the stall-control flap may be compared with the usual split flap. The split flap, of course, produces marked gains in $C_{L_{max}}$ but the stalling angle is little affected and the severity of the sudden drop in lift is markedly increased.

Figures 4, 5, 6, and 7 show the possibility of combining the two types of flap in order to realize the desirable characteristics of both. Here again the 12° deflection of the stall-control flap (fig. 5) proved the most effective in that the rounded-type lift-curve peak could be maintained up to a split-flap deflection of 45°. This combination burbles approximately 9° earlier than the same airfoil without the stall-control flap and gives a C_L for $\alpha = 0^\circ$ of 1.7 and a $C_{L_{max}}$ of 2.37. This value corrects to a section maximum lift coefficient $c_{l_{max}} = 2.54$. It should be remembered, however, that the stall of the section should not be expected to be as gradual as the stall of the tested rectangular wing formed from the same section.

APPLICATION TO WING DESIGN

Tapered Wings

Upson and Thompson (reference 7) have indicated that highly tapered wings, 5:1 or more, are generally aerodynamically desirable when the wings are adjusted to equal structural efficiency and when the variation of $C_{L_{max}}$ with taper is not taken into account. This result was not anticipated by the many engineers who considered a reasonably close approach to the elliptical wing to be the best design. The elliptical wing is aerodynamically superior when wings of equal area and span are compared but, if wings of equal structural weight are compared, the increased span possible through the use of a high taper ratio more than compensates for the losses associated with the departures from the elliptical load distribution.

A loss of maximum lift is, however, associated with high taper ratios. A brief analysis made at the N.A.C.A. laboratory and reported at the 1936 Manufacturers' Conference indicated, when the maximum-lift variation was taken into account on the assumption that variable twist or some other device such as the stall-control flap is not employed to avoid the loss, that the taper ratio cannot advantageously be carried much beyond 3:1 and that, even with moderate tapers, these wings are open to the objection that tip-stalling difficulties are likely to be encountered.

On the other hand, wing stiffness in relation to flutter, aside from strength, may become a very important consideration. Wing stiffness has not been adequately considered in any of the analyses, but it is apparent that such considerations would strongly favor high taper ratios. Those considerations were instrumental in bringing about the present investigation directed toward the avoidance of the maximum-lift losses and the tip-stalling difficulties, aerodynamic characteristics of highly tapered wings that block the realization of their structural advantages. How these difficulties with highly tapered wings may be minimized through the use of the stall-control flap is best brought out by means of an example.

Example

A wing of 40-foot span, aspect ratio 10, taper ratio 4, and a landing speed of approximately 65 miles per hour has been chosen for the example. Wing sections of the 230 series are employed and, for simplicity, the section thicknesses are considered to vary only from 11 to 14 percent of the chord so that variations of $c_{l_{max}}$ with section thickness are unimportant. The analysis in any case is made by the methods of references 2, 8, and 9.

Plain wing.- The methods of reference 2 are first employed to predict the variation of the lifting capabilities $(c_{l_{max}})$ of the sections. Allowance is thus made for the variation of Reynolds Number along the span (from 3.9 to 1.2 x 10^6 between the root and the section at 0.9 semispan).

The result is indicated by the dotted line in figure 8. The distribution of c_l, as shown by the solid curve in the figure, is found from the L_a tables of reference 8 or 9 after multiplying the corresponding c_{l_a} values by a suitable factor. The tabulated values are for $C_L = 1$, and the factor (1.28) is chosen to bring the solid curve up to the dotted one. At this point the local lift c_l has reached the local capability $c_{l_{max}}$ and stalling may be expected to begin. The factor 1.28 gives, of course, the corresponding wing lift coefficient C_L at which stalling begins. Little is known about the relation of this C_L value to $C_{L_{max}}$, but certain experiments and a few preliminary flight tests have indicated that this C_L value at which stalling begins either approximates $C_{L_{max}}$ or is effectively $C_{L_{max}}$ when tip stalling is involved because the airplane cannot be maintained in steady flight at higher values of C_L owing to the loss of control associated with the tip stalling. In fact, the predicted value may actually be too high when it is based on a $c_{l_{max}}$ curve of a frequently encountered type for which occasional or intermittent stalling may be present at a considerably lower value than that indicated by $c_{l_{max}}$.

In any event, the results indicate that stalling will begin near the 0.85 station at a wing lift coefficient approximately $C_{L_{max}} = 1.28$. The tip stalling and reasons for it are thus clearly brought out by figure 8 and the loss of $C_{L_{max}}$ associated with the high taper may be appreciated by comparing, for example, the wing maximum lift coefficient 1.28 with the root section maximum lift coefficient 1.61.

Partial-span flap.- The example is now extended to include the application of a partial-span split flap. The flap, 20 percent c, deflected 45°, and partial span as indicated on the plan-form diagram in figure 9 is considered. The c_l distribution (fig. 9) is found by the method of reference 9 by adding together suitable proportions of the c_{l_a} and c_{l_b} distributions. The pertinent section lift curves for the various sections are included in figure 10.

It is apparent that the lifting capabilities more than ever exceed the actual lift coefficients over the central or flapped portion. The results suggest that stalling will begin just outboard of the flap end and at a wing lift coefficient near $C_L = 1.61$. Little is known in this case, however, about the stall - how it would progress over the tip portion, how it would affect the lateral control, and to what extent this simplified theory may be in error owing mainly to the neglect of complications resulting from the three-dimensional character of the flow near the flap end. Results in better accord with experiment would probably be obtained if the break in the dotted curve indicating the loss of lifting capabilities at the flap end were faired out over a spanwise distance equal to one or two flap chords. These matters require further experimental investigation; nevertheless, the result $C_L = 1.61$ may be compared with $c_{l_{max}} = 2.38$ at the center section to indicate very roughly the loss of maximum lift associated with the high taper and partial-span flap.

Stall-control flap.- The application of the stall-control flap will now be considered. It is applied to only a short portion (26 percent) of the wing near the center span in order to permit its use without the addition of much structural weight and complication. As shown by the results in figure 11, center stalling may now be expected to develop, owing partly to the decrease of lifting capabilities over the center portion covered by the stall-control flap and partly to the building up of the lift associated with the large-chord flap deflection of 12°. As compared with the preceding example with the split flap only, the gain in lift, when stalling is equally likely to start at the tip, is shown by the shaded area. The lift in each case is adjusted so that tip stalling is equally likely as judged by the coincidence in the region of the tip of the heavy c_l curve and the light curve representing the preceding case. The gain is therefore twofold. Not only is the tendency toward the desired center stall of the gradual type realized, but the corresponding wing lift C_L is increased, as shown by the shaded area, from 1.61 to 1.7. Thus the objection to certain methods (sharp leading edges, small or inefficient fillets, or other spoiler devices) previously used to bring about gradual and early center stalling through some loss of maximum lift has been overcome.

Incidental Advantages

Some secondary advantages arising from the use of the stall-control flap should also be mentioned. For flying boats or airplanes with tricycle landing gears, take-off difficulties may be reduced owing to the large lift coefficients that may be realized with the airplane in approximately the level attitude. The improved lateral stability at the stall associated with the flat-top lift curve has been mentioned. Improved lateral control may also be secured. When a large drop in lift occurs in passing from the inner to the outer or aileron portion of the wing, the shed vorticity tends to cause the aileron portion of the wing to operate in the associated region of induced upwash. When the net induced velocities on the wing section are in the direction corresponding to an upwash, the local lift vector is sloped forward. Hence, when the lift is increased by a displacement of the aileron, the forward component is also increased, tending to produce, in turn, a favorable induced yawing moment. This characteristic, that is, the loss in lift that may be provided by excess flap deflections inboard of the ailerons, may allow the use of drooped ailerons, which have previously been avoided on account of their large adverse induced yawing moments although, of course, the drooping of the ailerons tends to remove the desired lift change. Calculations such as those of the foregoing example indicate that the increased lifting capabilities associated with the drooped ailerons, while influencing directly only a small portion of the wing, may in some cases yield a considerable gain in $C_{L_{max}}$ by allowing the entire wing to operate at a higher lift coefficient.

Structure

At first sight the structural problems associated with the 0.6c flap appear formidable. Certain types of wing structure, such as single spar with torsion leading edge, or other types that at present seem to be coming into favor, with the main structure well forward and with fabric-covered trailing-edge portions, permit the application of the large-chord flap without major changes in the structure. In any event, the ribs must cantilever from the spar, and whether or not the large flap is moved makes very little difference in the loads on the rib members at the spar because these are a function almost entirely of the displacement of the small-chord high-lift flap at the trailing edge. These same loads must be dealt with when the large flap is not present. The complication is only that of making the structure movable under these loads.

Problems associated with the operating mechanism should not be very difficult when a short-span flap, as in the preceding example, is employed. With a stall-control flap covering a considerable portion of the span, which in some cases appears advantageous, the best solution apparently involves the use of many hinges and hydraulic-jack units distributed along the spar.

Other Devices

There remain to be considered other methods of avoiding the tip stall. Some washout may be employed to advantage and, for moderate taper, the small washout that is allowable without serious detrimental effects (reference 8), together with a small change in profile to a higher lift (430 series, for example) though less efficient section, may be employed over the tip portion. Some loss is always involved, however, and the loss rapidly becomes large as the taper is increased.

The other possibility that has previously been suggested (reference 10) is the use of leading-edge slots over the outer portion of the wing. As indicated in reference 10 and as calculations made in the preceding example readily show, the method should be effective; but many objections have been advanced to the use of movable tip slots. Whether or not the increased maximum lift compensates the additional drag, weight, danger of improper functioning, and complication remains a question. Furthermore, if the answer definitely favors the use of slots, then it appears that this type of section may be considered for use throughout the entire wing rather than only for the tip portions, and the problem of tip stalling then returns in its original form. Its solution by the omission of the leading-edge slots over the central portions becomes almost the equivalent of introducing sharp leading edges or other spoiler devices on the original wing. From this viewpoint, an aerodynamic loss is accepted to avoid the tip stalling. It then appears that, even though slots should prove to be generally advantageous, the stall-control flap used together with the slotted sections may remain the most efficient means of avoiding the tip stall of highly tapered wings.

Viewed from considerations of improving existing wing types, however, either the sharp leading edges or the addition of leading-edge slots at the tips may be satisfactory. The reduced lifting capabilities near center span associated with the spoiler devices (sharp leading edges, inefficient fillets, motor nacelles, or the absence of leading-edge slots) do not necessarily exert a primary effect on the wing maximum lift. With highly tapered wings the lifting capabilities of the center sections may be reduced to a point corresponding to equal likelihood of center and tip stalling without appreciably affecting the wing maximum lift although, as compared with wings having less taper or a device giving effectively a variable twist such as the stall-control flap, some loss of maximum lift must be accepted.

On the other hand, when the wing maximum lift is determined primarily by the lifting capabilities of the tip sections, the criterion for the selection of these sections must be modified. Sections that would otherwise be judged inferior, owing to objectionable complications or to a somewhat excessive drag, should be considered. Such sections may prove acceptable as applying to only a small part of the wing because they may permit an increase of lift over the whole of the wing.

CONCLUDING REMARKS

An aerodynamically satisfactory solution to the problem of the stalling of tapered wings now appears to be available.

It is, of course, realized that the application of the stall-control flap adds difficulties and complications. Whether or not the result is worth the expense must be decided by the designer in relation to a particular project under consideration. It is hoped that the preliminary data presented herein will be of assistance in such design studies.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 14, 1937.

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Figure 1.- Effect of upper surface curvature at hinge. N.A.C.A. 23012 with 0.6c flap at 12° and 0.2c ordinary flap at 15°. Rectangular wing, aspect ratio 6, free air.

Figure 2.- Airfoil with stall-control flap. N.A.C.A. 23012 with 0.6c flap. Rectangular wing, aspect ratio 6, free air.

Figure 3.- Airfoil with split flap. N.A.C.A. 23012 with 0.2c split flap. Rectangular wing, aspect ratio 6, free air.

Figure 4.- N.A.C.A. 23012 with 0.6c flap at 8° and 0.2c split flap. Rectangular wing, aspect ratio 6, free air.

Figure 5.- N.A.C.A. 23012 with 0.6c flap at 12° and 0.2c split flap. Rectangular wing, aspect ratio 6, free air.

Figure 6.- N.A.C.A. 23012 with 0.6c flap at 16° and 0.2c split flap. Rectangular wing, aspect ratio 6, free air.

Figure 7.- Stall-control and plain flaps. Rectangular wing, wing, aspect ratio 6, free air.

Figure 8.- Plain wing. Plan form and distribution of lift coefficient and lifting capability.

Figure 9.- Wing with partial-span flap. Plan form and distribution of lift coefficient and lifting capability.

Figure 10.- Section data for the calculation of the partial-span flap used in the example (R_e approximately 8,000,000). The lift peaks indicate how the section maximum lift correction is made.

Figure 11.- Wing with stall-control flap. Plan form and distribution of lift coefficient and lifting capability.

TABLE I

CHARACTERISTICS OF N.A.C.A. 23012 AIRFOIL WITH STALL-CONTROL AND SMALL-CHORD FLAPS

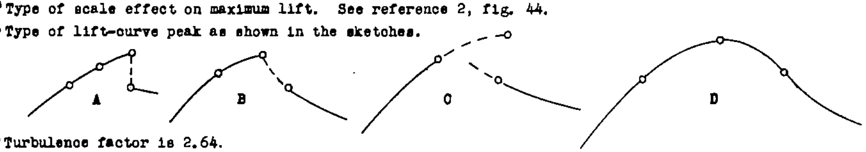
Airfoil	0.6c flap deflection (deg.)	Small-chord flap: Flap-chord ratio	Small-chord flap: Type	Small-chord flap: Deflection (deg.)	Classification: Chord	Classification: PD	Classification: SE	Classification: $C_{L_{max}}$	Fundamental section characteristics: Effective Reynolds Number (millions)	$c_{l_{max}}$	α_{l_o} (deg.)	a_o (per deg.)	$c_{l_{opt}}$	$c_{d_{o_{min}}}$	$c_{m_{(a.c.)_o}}$	a.c., (percent c from c/4): Ahead	a.c., (percent c from c/4): Above	Derived and additional characteristics that may be used for structural design: $\frac{c_{l_{max}}}{c_{d_{o_{min}}}}$	c.p. at $c_{l_{max}}$ (percent c)	Wing characteristics A = 6; round tips: a_e (per radian)	Wing characteristics A = 6; round tips: $C_{D_{min}}$
N.A.C.A.					(1)	(2)	(3)	(4)	(5)	(6)	(7)	(6,8)	(6)	(6)	(10)						
23012	0	-	-	-	A	C12	D2	A	8.4	1.74	-1.2	0.100	0.08	0.0070	-0.008	1.2	7	249	25	4.34	0.0071
23012	4	-	-	-	A	-	-	B	8.5	1.73	-4.6	.097	.3	.0080	-.035	-	-	216	28	4.24	.0085
23012	8	-	-	-	A	-	-	D	8.5	1.75	-8.1	.098	.2	.0089	-.061	-	-	197	29	4.28	.0093
23012	12	-	-	-	A	-	-	D	8.4	1.77	-11.9	.096	.3	.0098	-.095	-	-	181	32	4.20	.0105
23012	16	-	-	-	A	-	-	D	8.3	1.74	-15.1	.102	.3	.0108	-.12	-	-	161	33	4.41	.0114
23012	20	-	-	-	A	-	-	D	8.4	1.79	-18.7	.099	.4	.0121	-.15	-	-	148	34	4.32	.0133
23012	0	0.2	Split	15	A	-	D2	A	8.4	2.09	-5.3	.104	.4	.0280	-.10	-	-	75	31	4.47	.0281
23012	0	.2	...do...	30	A	-	D2	A	8.4	2.33	-9.3	.103	-	[9].072	-.1[illegible]	-	-	-	34	4.44	-
23012	0	.2	...do...	45	A	-	D2	A	8.5	2.50	-12.4	.097	-	[9].120	-.2[illegible]	-	-	-	34	4.24	-
23012	0	.2	...do...	60	A	-	D2	A	8.5	2.53	-14.3	.095	-	[9].165	-.2[illegible]	-	-	-	35	4.18	-
23012	8	.2	...do...	15	A	-	-	D	8.4	2.09	-12.1	.104	.3	.0291	-.16	-	-	72	33	4.47	.0296
23012	8	.2	...do...	30	A	-	-	D	8.5	2.38	-16.1	.102	-	[9].075	-.25	-	-	-	35	4.41	-
23012	12	.2	...do...	15	A	-	-	D	8.4	2.07	-16.0	.103	.5	.0303	-.19	-	-	68	34	4.44	.0312
23012	12	.2	...do...	30	A	-	-	D	8.3	2.38	-20.0	.102	-	[9].075	-.27	-	-	-	36	4.41	-
23012	12	.2	...do...	45	A	-	-	D	8.3	2.54	-22.9	.098	-	[9].120	-.32	-	-	-	37	4.28	-
23012	12	.2	...do...	60	A	-	-	B	8.4	2.62	-25.4	.093	-	[9].163	-.33	-	-	-	36	4.11	-
23012	16	.2	...do...	15	A	-	-	C	8.5	2.01	-19.4	.104	.6	.0310	-.22	-	-	65	36	4.47	.0321
23012	16	.2	...do...	30	A	-	-	A	8.4	2.40	-23.2	.105	.1	[9].075	-.30	-	-	-	38	4.51	-
23012	16	.2	...do...	45	A	-	-	B	8.4	2.54	-26.5	.099	.1	[9].120	-.35	-	-	-	38	4.32	-
23012	16	.2	...do...	60	A	-	-	A	8.4	2.62	-28.4	.094	.2	[9].160	-.36	-	-	-	38	4.14	-
23012	12	.2	Ordinary	15	A	-	-	D	8.4	1.98	-19.1	.087	.2	.0150	-.23	-	-	132	35	3.89	.0156
23015	12	.3	...do...	45	A	-	-	D	8.3	2.24	-30.4	.079	.2	[9].135	-.37	1.1	6	-	39	3.60	-
23015	6	.2	...do...	60	A	-	-	D	8.3	2.46	-24.0	.087	-.1	[9].130	-.35	-	-	-	37	3.89	-

[1] Type of chord. A refers to a chord defined as a line joining the extremities of the mean line of the airfoil without flaps.

[2] Type of pressure distribution.

[3] Type of scale effect on maximum lift. See reference 2, fig. 44.

[4] Type of lift-curve peak as shown in the sketches.



[5] Turbulence factor is 2.64.

[6] These data have been corrected for tip effect.

[7] Angle of zero lift obtained from linear lift curve approximating experimental lift curve.

[8] Slope obtained from linear lift curve approximating experimental lift curve.

[9] $c_{d_{o_{min}}}$ lay outside range of lift coefficients covered in these tests. Value of $c_{d_{o_{min}}}$ shown applies approximately over entire useful range of lift coefficients.

[10] $c_{m_{(a.c.)_o}}$ is taken about the aerodynamic center of the airfoil without flaps and is the average value.

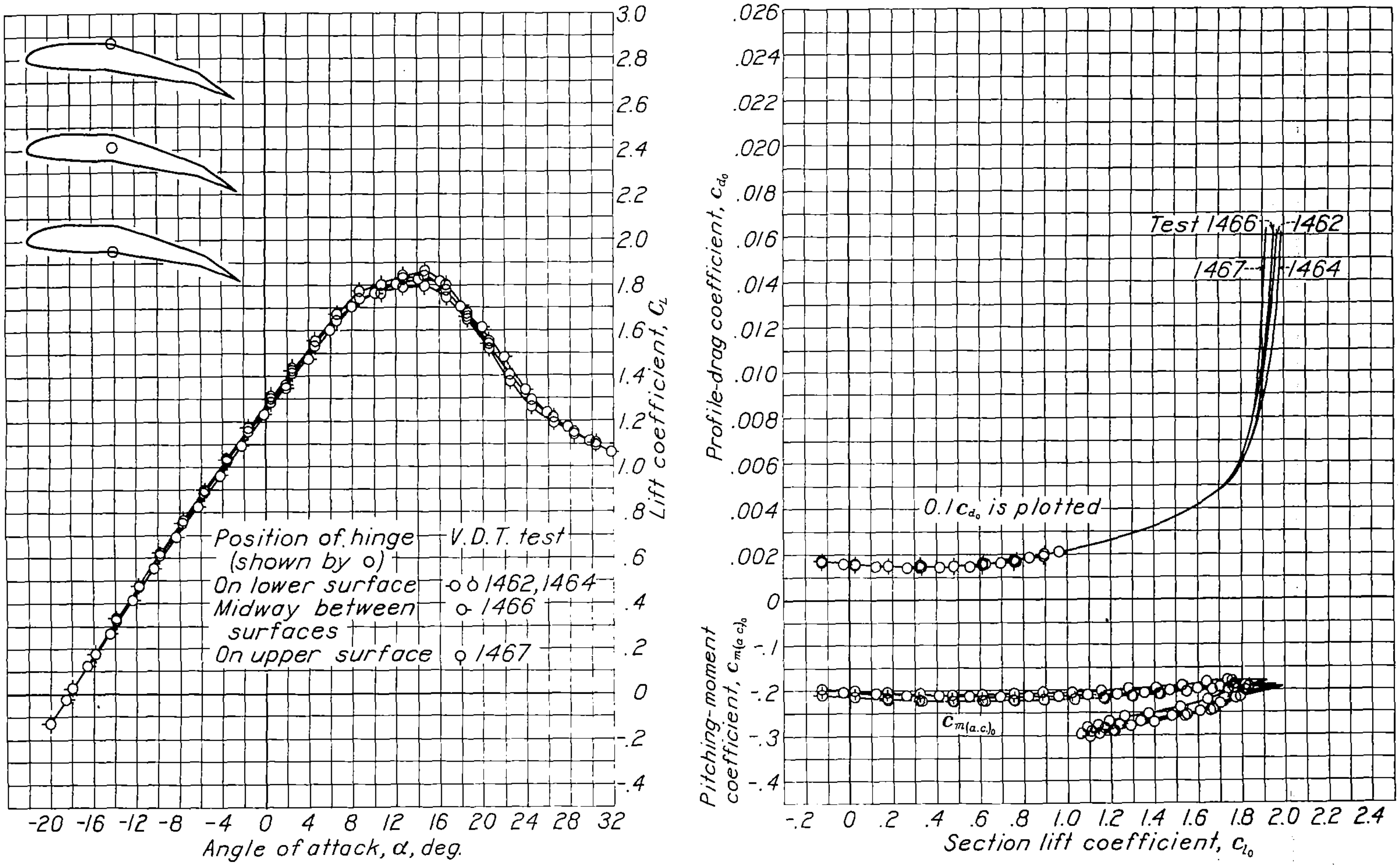

Position of hinge (shown by o)
V.D.T. test
On lower surface 1462, 1464
Midway between surfaces 1466
On upper surface 1467
Lift coefficient, C_L
Angle of attack, α, deg.
Profile-drag coefficient, c_{d_0}
Test 1466 1462
1467 1464
$0.1c_{d_0}$ is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 1

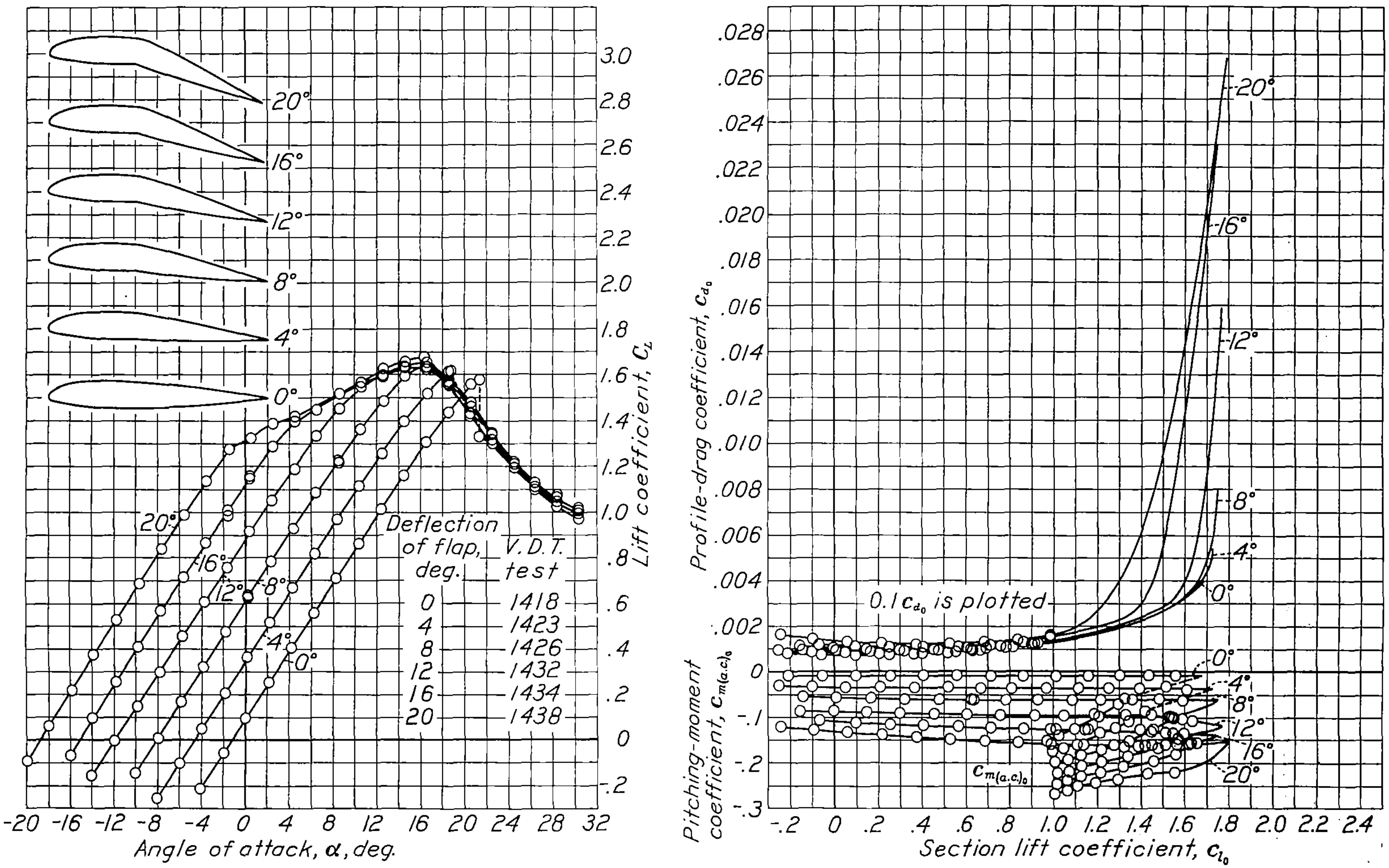

20°
16°
12°
8°
4°
0°
Lift coefficient, C_L
Angle of attack, α, deg.
Deflection of flap, deg.
V.D.T. test
0 1418
4 1423
8 1426
12 1432
16 1434
20 1438
Profile-drag coefficient, c_{d_0}
$0.1\,c_{d_0}$ is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 2

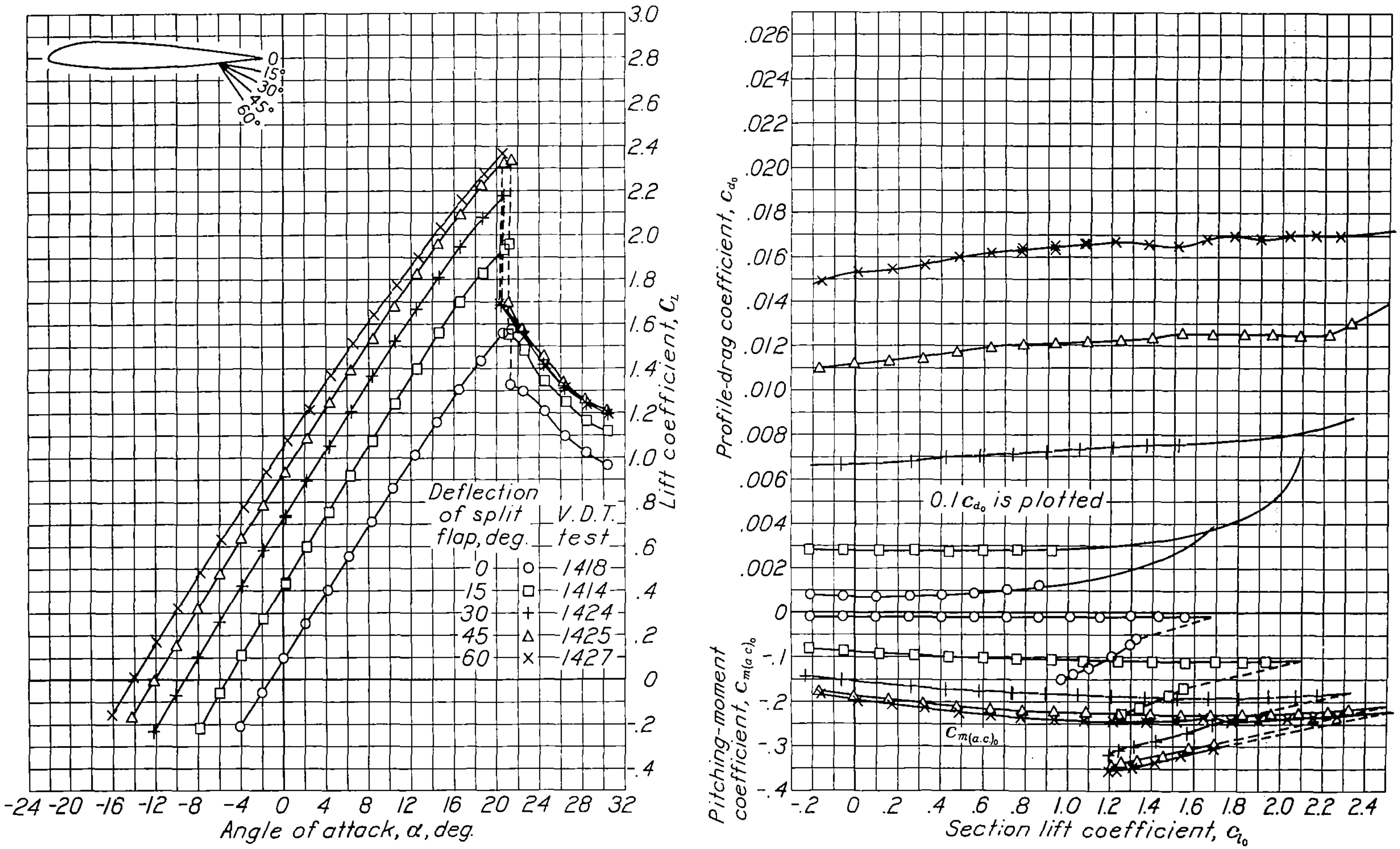

0
15°
30°
45°
60°
Lift coefficient, C_L
Angle of attack, α, deg.
Deflection of split flap, deg.
V.D.T. test
0 — ○ — 1418
15 — □ — 1414
30 — + — 1424
45 — △ — 1425
60 — × — 1427
Profile-drag coefficient, c_{d_0}
0.1 c_{d_0} is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 3

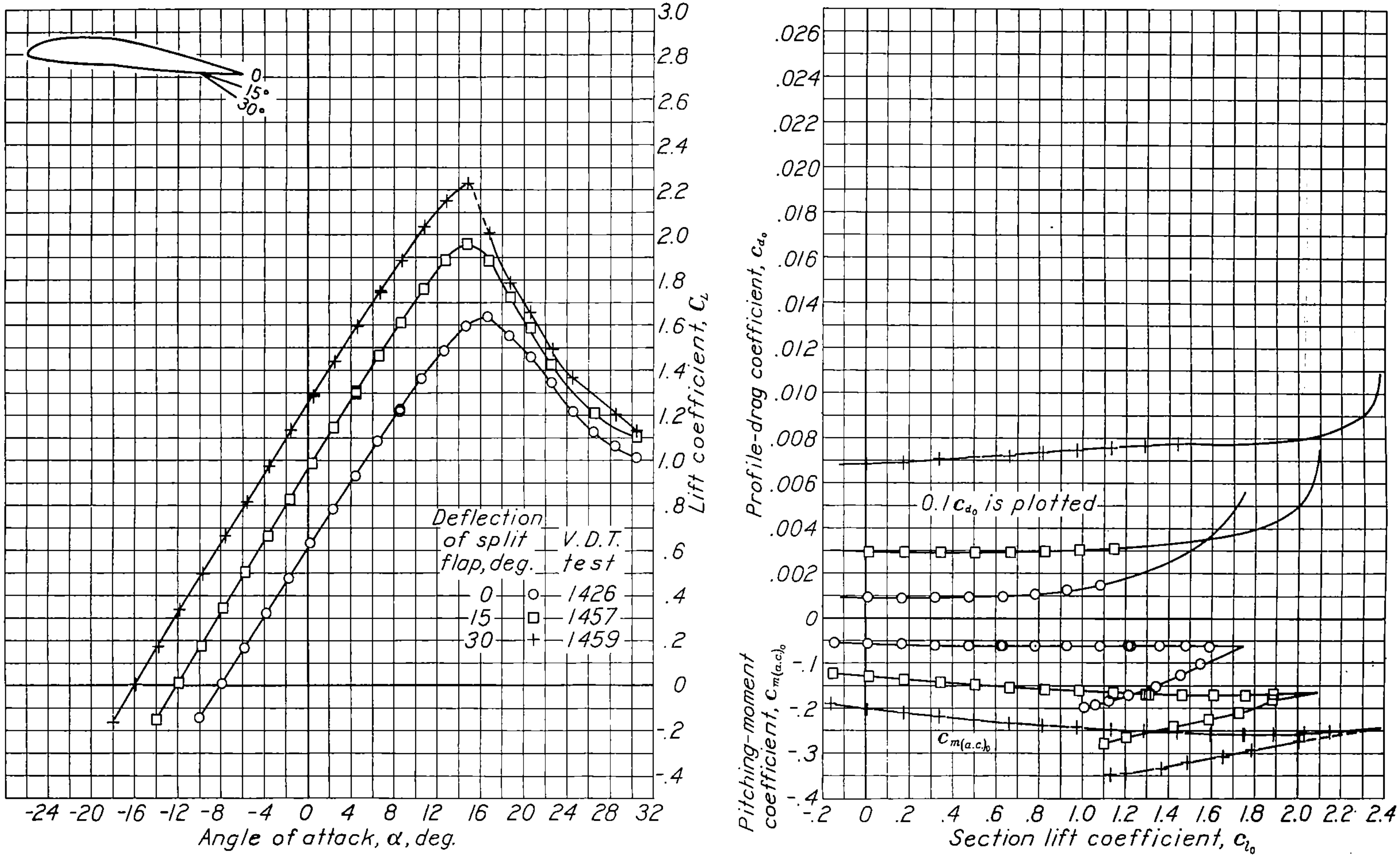

0°
15°
30°
Deflection of split flap, deg.
V.D.T. test
0 — ○ — 1426
15 — □ — 1457
30 — + — 1459
Lift coefficient, C_L
Angle of attack, α, deg.
Profile-drag coefficient, c_{d_0}
0.1 c_{d_0} is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 4

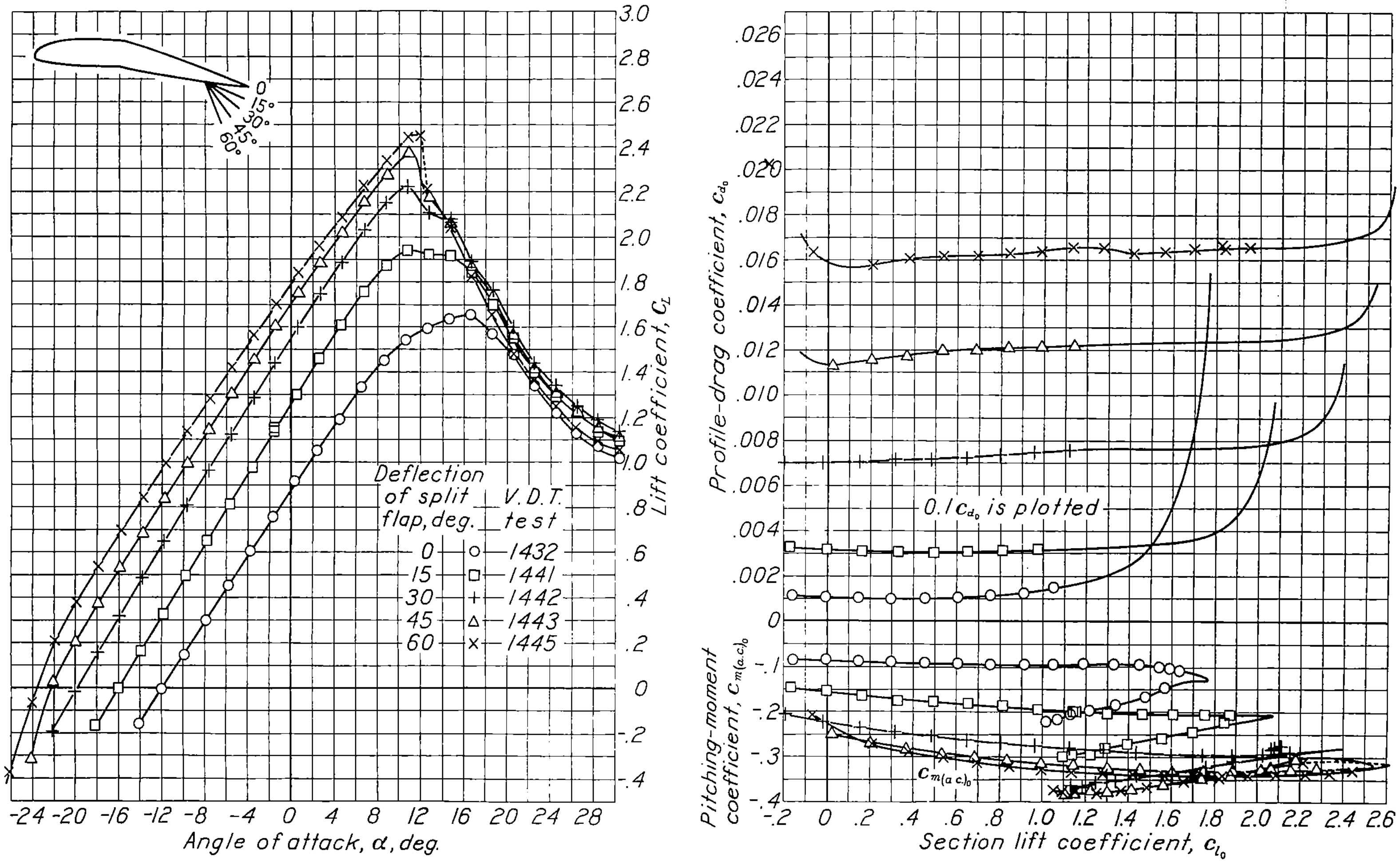
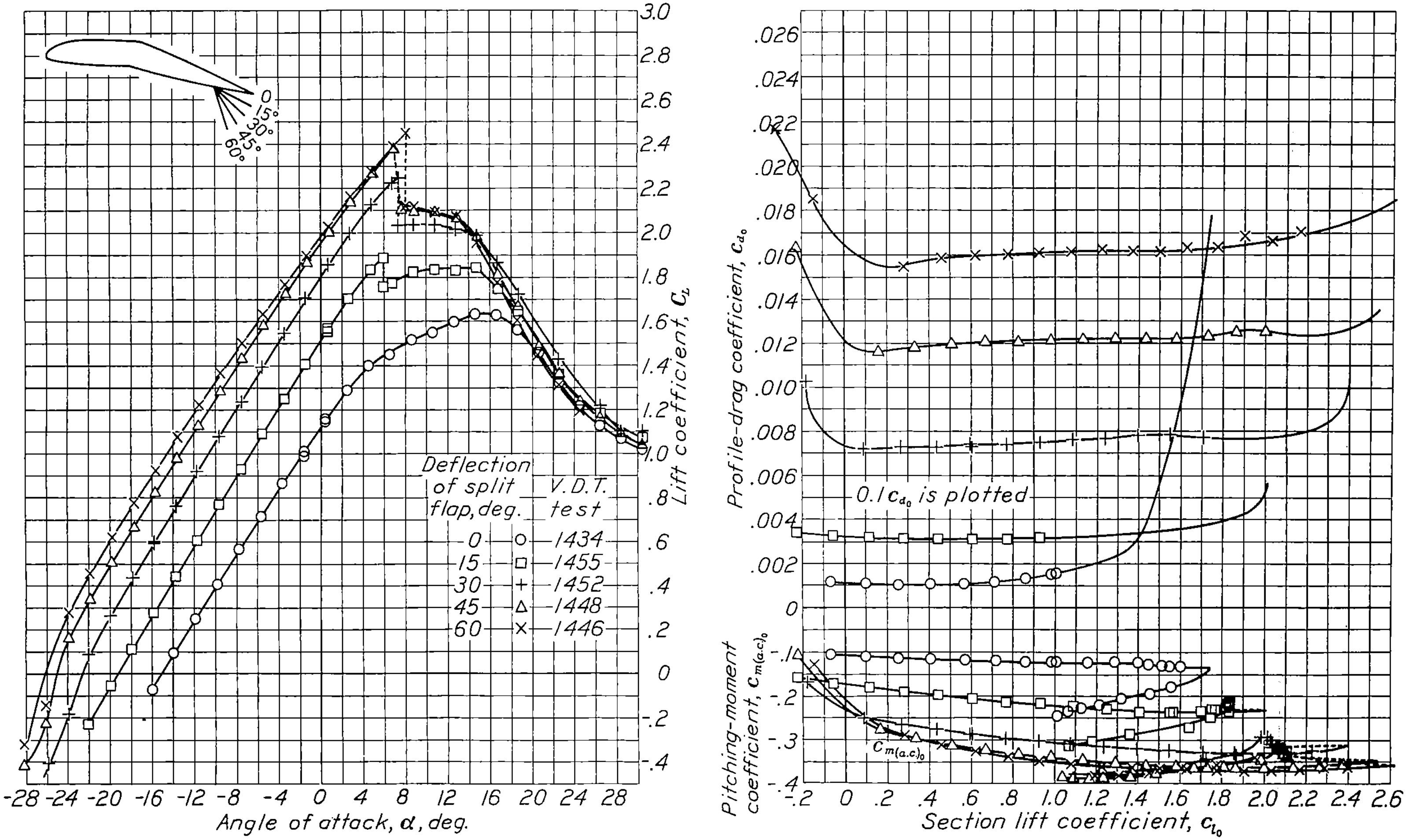

0°
15°
30°
45°
60°
Deflection of split flap, deg.
V.D.T. test
0 — ○ — 1432
15 — □ — 1441
30 — + — 1442
45 — △ — 1443
60 — × — 1445
Lift coefficient, c_L
Angle of attack, α, deg.
Profile-drag coefficient, c_{d_0}
$0.1 c_{d_0}$ is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 5



0
15°
30°
45°
60°
Deflection of split flap, deg.
V.D.T. test
0 ○ 1434
15 □ 1455
30 + 1452
45 △ 1448
60 × 1446
Lift coefficient, C_L
Angle of attack, α, deg.
0.1 c_{d_0} is plotted
Profile-drag coefficient, c_{d_0}
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 6

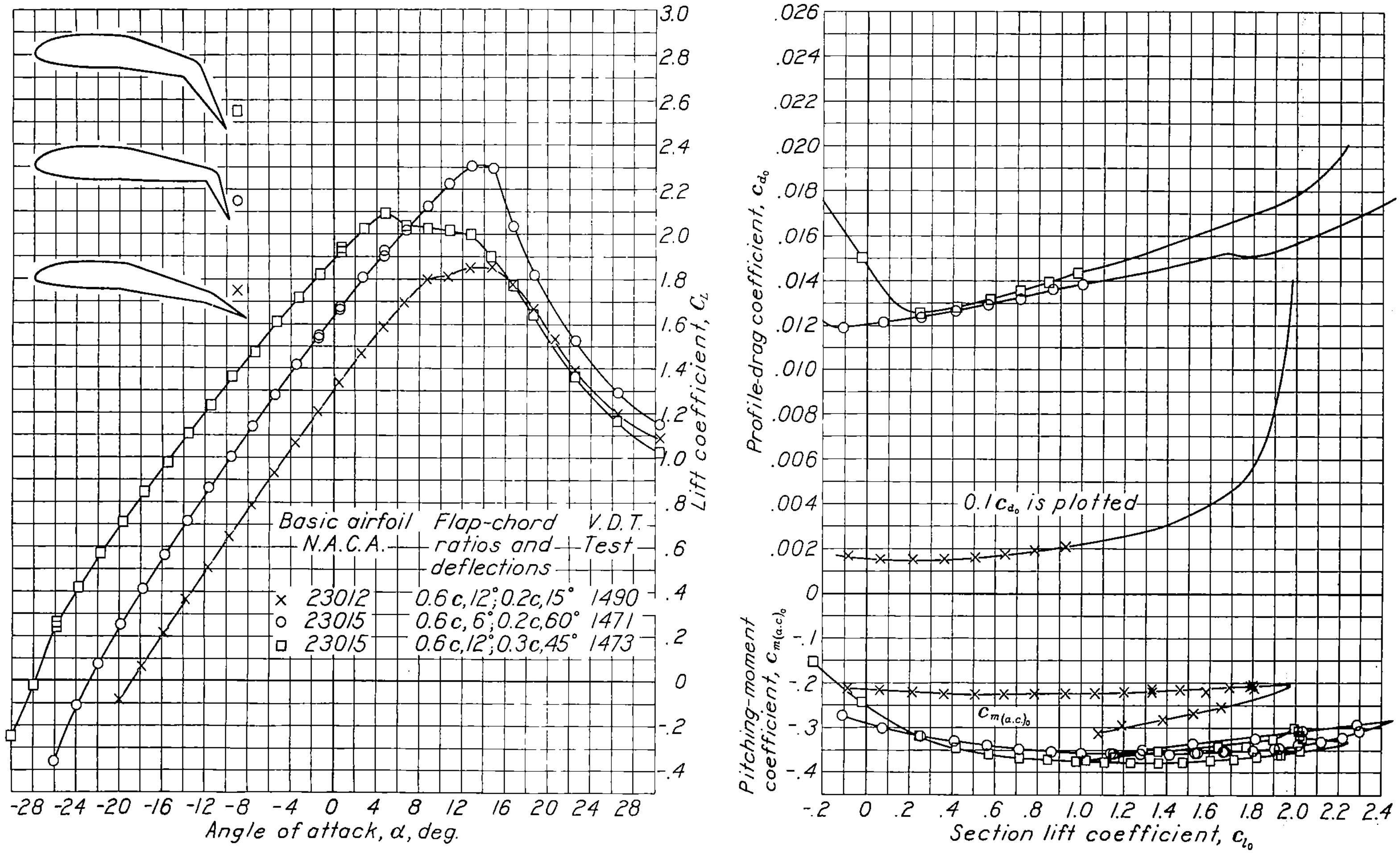

Lift coefficient, C_L
Angle of attack, α, deg.
Basic airfoil N.A.C.A.
Flap-chord ratios and deflections
V.D.T. Test
× 23012 0.6 c, 12°; 0.2c, 15° 1490
○ 23015 0.6 c, 6°; 0.2c, 60° 1471
□ 23015 0.6 c, 12°; 0.3c, 45° 1473
Profile-drag coefficient, c_{d_0}
0.1 c_{d_0} is plotted
Pitching-moment coefficient, $c_{m(a.c.)_0}$
$c_{m(a.c.)_0}$
Section lift coefficient, c_{l_0}

Figure 7

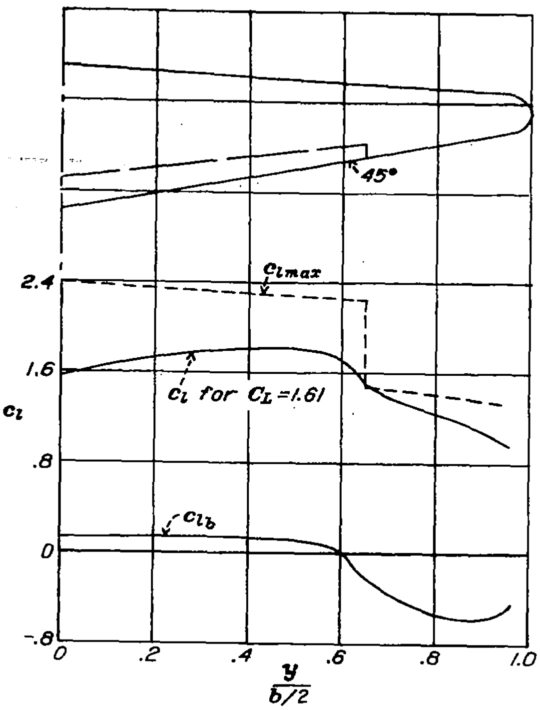


Figure 9

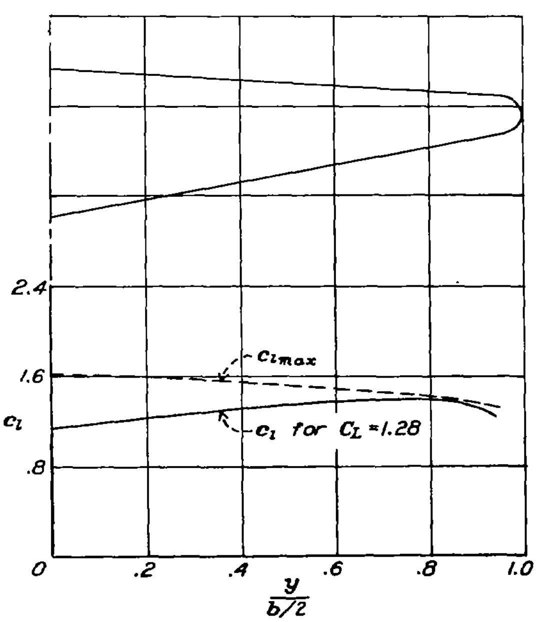


Figure 8

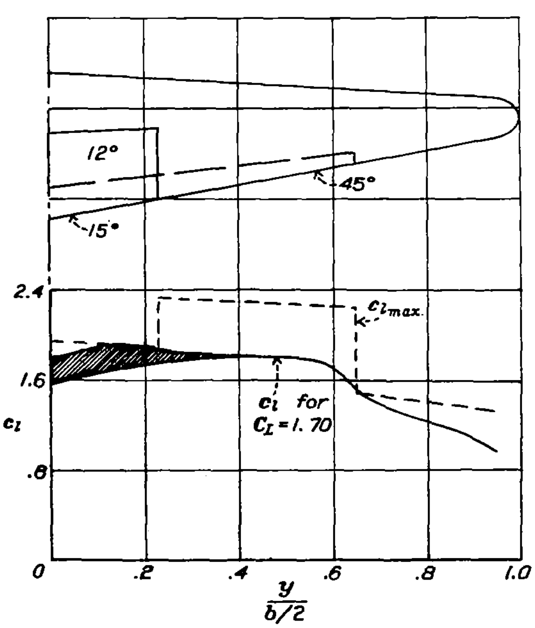
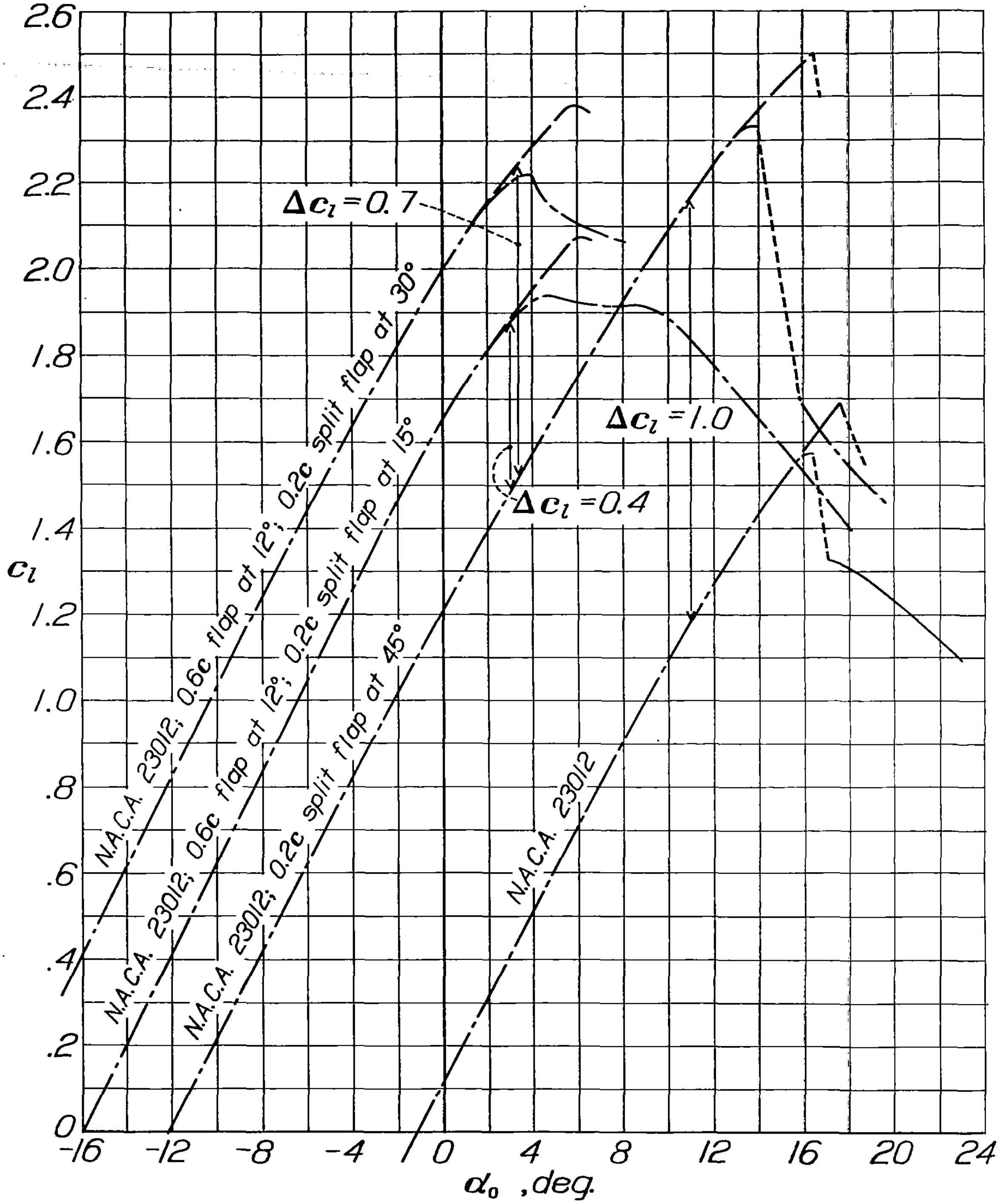


Figure 11


2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
c_l
-16
-12
-8
-4
0
4
8
12
16
20
24
α_0 ,deg.
Δc_l =0.7
Δc_l =1.0
Δc_l =0.4
N.A.C.A. 23012; 0.6c flap at 12°; 0.2c split flap at 30°
N.A.C.A. 23012; 0.6c flap at 12°; 0.2c split flap at 15°
N.A.C.A. 23012; 0.2c split flap at 45°
N.A.C.A. 23012